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Air emissions scenarios from ethanol as a gasoline oxygenate in Mexico City Metropolitan Area

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ABSTRACT

The Mexican Biofuel Introduction Program states that during year 2010 the three biggest Mexican cities will have a gasoline blending with 6% ethanol available for all gasoline on-road vehicle fleet. Also in 2010 Mexican government has programmed to start the substitution of Tier 1 – the adopted US emission standards – by Tier 2, which are more stringent emission standards for motor vehicles and gasoline sulfur control requirements. How will the air emissions in the Mexico City Metropolitan Area (MCMA) be modified by using this blending? Four scenarios up to year 2030 were constructed and simulated using the Long-Range Energy Alternatives Planning model. Beginning with a BAU or reference scenario, in this scenario the current available fuel is a blending composed by 5% methyl tertiary butyl ether and 95% gasoline (MTBE5). Then, three alternative scenarios that use ethanol as an oxygenate are considered, one with the already programmed E6 blending (6% anhydride ethanol, 94% gasoline), for the sake of comparison the E10 blending (10% anhydride ethanol, 90% gasoline), and the other alternative to compare, ETBE13.7 (13.7% ethyl tertiary butyl ether, 86.3% gasoline; where ETBE is an ether composed by 48% anhydride ethanol and 52% isobutene). Emissions of carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NOx), particulate matter (PM10), sulfur dioxide (SO_2), total hydrocarbons (THC), benzene, formaldehyde, acetaldehyde and 1,3-butadiene were calculated using emission factors previously calculated using the adapted US-EPA computer model called MOBILE6-Mexico. Results show that Tier 1 and Tier 2 standards effectively lowers all emissions in all studied scenarios with the exception of PM10 and CO_2 emissions. The alternative scenario E10 has the most total avoided emissions by weight but it is not the best when considering some individual pollutants. The greatest environmental benefit of ethanol in its final use as a gasoline oxygenate is for avoiding CO_2 emissions.

Contents

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1. Introduction

Atmospheric emissions of polluting agents in urban centers are directly related to negative health effects in its inhabitants [1]. According to an evaluation of the World Health Organization [2], every year, more than two million premature deaths in urban areas can be attributed to the exhaust gases of fossil fuels. According to Fuglestvedt et al. [3], transport sector is the most important worldwide source of exhaust gases of fossil fuels, principally nitrogen oxides (NOx) 37%, total hydrocarbons (THC) 19%, carbon monoxide (CO) 18%, sulfur dioxide (SO_2) 2% [4] and particulate matter (PM10) 6% [5]. Finally, it contributes worldwide to the liberation of 21% of total carbon dioxide (CO_2) emissions.

Mexico City Metropolitan Area (MCMA) is not exempted from this environmental problem. Not less than 40% of urban population is exposed to air pollution levels above standards [6]. According to [7], in 1994 airborne contamination through particles and tropospheric ozone could cause 4919 deaths in MCMA. Mobile sources contributed with this problem with 19% of the 31,380 tonnes of particulate matter (PM) in that year [8]. In addition, transport sector in MCMA is the main source of antropogenic emissions of CO_2 (56%), CO (99%) and NOx (82%), primarily due to on-road vehicles [9–11]. This air quality deterioration causes respiratory and cardiovascular diseases [12], attributed to the synergetic action of the following criteria pollutants: particulate matter smaller than 10 μm (PM10), sulfur dioxide (SO_2), carbon monoxide (CO), nitrogen oxides (NOx) and hydrocarbons (HC) (these last tree are also tropospheric ozone precursors); toxic polluting agents like: benzene, 1,3-butadiene, formaldehyde and acetaldehyde. In total the MCMA transport sector contributes with 57% of total emissions due to fossil fuel combustion [11].

Worldwide actions have been taken to reduce vehicle polluting emissions and consequently decrease their effects in human health, such as standards and energy efficiency regulations, fuel quality control, introduction of more demanding emissions standards and introduction of vehicles with new technologies and alternative fuels [6]. Energy efficiency regulations consider an increase in the fuel economy. Examples of these regulations are the Corporate Average Fuel Economy (CAFE) regulations in the USA. Fuel control refers to lead and sulfur content in fuels, as well as to limit the Reid Vapor Pressure (RVP) in order to reduce the evaporative emissions. In particular it is expected a shift toward low-CO_2 fuels as ethanol [13] and the adoption of new vehicle technologies beginning with hybrids, plug-in hybrids, and transitioning to hydrogen fuel cell and battery electric vehicles over time [14–16].

The emission standards for each type of vehicle that limit the amount of pollutant emissions are being fulfilled by installing emission control technologies, like the catalytic converter, which is the most widely used technology. Generally, the standards are dynamic, they keep evolving to more demanding standards that limit in an important way the air emissions.

Regarding new fuels available for air emissions mitigation, this option can replace completely or partially fossil fuels: gasoline and diesel. The search of new fuels must take into account, besides the problem of the atmospheric emissions, the problem of high oil dependency as a unique energy source for motor vehicles and additionally, the problem of the petroleum production decline [17]. Due to these reasons, the alternative fuels must reduce GHG emissions and their effects on the global warming of the planet and look for the sustainability of raw materials from which they will be obtained.

Ethanol is the most widely used alternative fuel in the transport sector, particularly in Brazil and the United States. It has been proposed to replace gasoline in a partial or complete way. The ethanol has been promoted as a clean and renewable fuel that reduces air pollution and global warming as a consequence of lowering GHG emissions. These reasons have been used to justify the fiscal incentives to the producers and the promulgation of energy bills for the promotion and the use of the ethanol throughout the world [13].

Ethylic alcohol or ethanol is a well known alcohol that can be obtained chemically from ethylene, a product of oil refinement, from ethane, a natural gas component or biologically through fermentable sugars, derived typically from starch crops, cellulose and other forms of vegetal biomass [18]. Due to the fact that ethanol can be produced from biomass, this biofuel has a renewable character. From now on, it will be assumed that the ethanol referred in this study is from biological origin, produced from crops or another organic material.

The findings of studies examining the use of ethanol as a gasoline substitute to reduce GHG emissions in the transport sector have been positive consensed. Nguyen et al. [19] affirms that ethanol can be produced in a renewable manner either if it is produced from cultivated crops as sugarcane or from cellulosic residues. However, there is a debate in whether or not ethanol can contribute to air pollution reduction as a gasoline substitute. The role of new emission control technologies incorporated into these studies is crucial. There are many studies and compilations on the atmospheric emissions from vehicles that use different volumetric ethanol-gasoline blendings [20–28], that present variable and sometimes contradictory results among them. Nevertheless, Schifter work [20] is crucial for the present article because he obtained experimentally emission factors of ethanol-gasoline blendings in Mexico City. In addition, the effect of emission standards and vehicle fleet renewal has not been explored in the great majority of these studies.

In the 1980s there were many urban air pollution problems in Mexico due to leaded gasoline, the national measure adopted in 1988 was the use of unleaded reformulated gasoline, after that the tendency has been to reduce the sulfur content in gasolines and diesel. In some Mexican urban centers vehicle inspection and maintenance programs were adopted, as well as improvements in road infrastructure [6], in particular in MCMA. In Mexico City since 1992 the local government has adopted through four air quality improvement programs – where PROAIRE 2002–2010 is the latest one [29] – many different actions like: restrictions on the use of vehicles older than 10 years to 1 day per week; renewal of public transport fleet, from small and medium-sized transit to high capacity public transportation; promotion of second story upper-deck freeways; implementing self-regulating programs to control pollutant emissions from industry sources, and finally the implementation of a gasoline vapor recovery program at all gasoline refueling stations [30].

Since 1999 Mexico has adopted the emission standards for motor vehicles previously applied to the United States called Tier 1 [31]. In the USA Tier 1 standards were designed to control criteria air pollutants in exhaust gases emitted from automobiles and light trucks (SUVs, pickup trucks, and minivans), and were used in the USA until 2004. Afterwards, from 2004 to 2009 Tier 2 was phased in, which consisted in a vehicle and gasoline sulfur program to control air pollution from motor vehicles by setting emissions standards and gasoline sulfur content requirements [32]. It has been proved that by lowering the average sulfur content of gasoline from 120 ppm to 30 ppm, emissions of tropospheric ozone precursors NOx and THC are also reduced [33]. Mexico has plans to adopt also Tier 2 standards, initially this adoption was programmed to enter into force by 2010, however the exact date will depend on the availability of ultra low sulfur gasolines. Pemex, the national oil company recently declared that they will not be capable to refine those gasolines before year 2015 [34].

The possibility to replace lead compounds by ethanol as a gasoline oxygenate was previously considered by the Mexican

government in 1988, some studies were performed [35], but that initiative was not realized. Nevertheless, in 2008 the "Law for the Promotion and Development of Biofuels" [36] mandates that the use of biodiesel and ethanol in motor vehicles has to be implemented through a Biofuels Introduction Program finally published in 2009 [37]. This program states that ethanol will be used as a gasoline oxygenate in a 6% volume proportion – known as E6 – and will be distributed in 3 major cities: Guadalajara (by the end of 2011), Monterrey and Mexico City and its metropolitan area by the end of 2012. It is worth to mention that this program does not involve the sugar cane production that is currently used for sugar production.

The purpose of this study is to determine the atmospheric emissions in the MCMA produced by the expected on-road gasoline motor vehicle fleet up to 2030, due to the combustion of current available gasoline (MTBE5) as a reference scenario and three ethanol oxygenates blendings in alternative scenarios E6, E10 and ETBE13.7. E6 was chosen because it is the official ethanol blending being introduced by the national program, E10 is the most widely used ethanol blending in the world and ETBE13.7 is the most easily substitutable blending, just by substituting MTBE by ETBE. Four long-range scenarios were constructed considering the restrictions involved in the American Air emission standards Tier 1 and Tier 2 that had been adopted or will be adopted by the Mexican government. All scenarios were simulated using LEAP model to obtain the evolution of the vehicle fleet, its energy consumption and polluting emissions. The polluting emissions were computed with the input of emissions factors data previously calculated with MOBILE6-Mexico for toxic air pollutants (benzene, formaldehyde, acetaldehyde and 1,3-butadiene), criteria air pollutants (carbon monoxide, nitrogen oxides, particles, sulfur dioxide and total hydrocarbons), and carbon dioxide the most important greenhouse gas.

2. Scenario construction

In this study the constructed scenarios represent a possible evolution of the motor vehicle fleet of the MCMA from year 2002 to year 2030. All scenarios are constructed considering the current emission control regulation Tier 1 until 2010, and thereafter Tier 2 regulation standard is programmed to enter into force, nevertheless the exact moment in which Tier 2 will be applied depends completely on the availability of gasoline with low sulfur content in Mexico.

The description of a possible future and its associated trajectory constitutes a scenario. Scenarios represent different images from future, constructing these future images helps us understand how the decisions and the actions taken today can have influence in the future. The scenario technique is an instrument of the prospective that allows reducing the degree of uncertainty in the decision-making. The uncertainty about the future evolution of the socioeconomic systems is absolutely inevitable. This is the reason why it is only possible to realize reconnaissance exercises of the future [38].

General assumptions:

- Year 2002 is considered the base year.
- The structure of the transport sector motor vehicle fleet in 2002 for the MCMA remains constant until 2030.
- The annual average growth rate (AAGR) of gasoline vehicles sales in the MCMA is 3%, that is the historical tendency from 1993 to 2003 [39].
- The survival profile is the same for all types of gasoline vehicles.
- The annual mileage traveled by each type of gasoline vehicle in the MCMA will stay constant in all the period.

The process of scenario construction begins with the construction of the reference scenario, also known as Business As Usual (BAU), where all gasoline motor vehicles will use as today MTBE5 (5% MTBE and 95% gasoline in percentage of volume). The MTBE (Metil Tertiary Butilene Ether) is the actual oxygenate in the gasoline consumed in the MCMA [20]. This article analyzes the substitution of MTBE by ethanol, which will be considered as the gasoline oxygenate in three alternative scenarios. In the first, all gasoline motor vehicles will use E6 (6% anhydrous or dehydrated ethanol and 94% gasoline in percentage of volume) [37]. In the second alternative scenario, ethanol is used as part of the compound ETBE (Ethyl Tertiary Butyl Ether), which actually contains 48% ethanol and 52% isobutene. And the blending used in all gasoline motor vehicles is ETBE13.7 (13.7% ETBE and 86.3% gasoline in percentage of volume). This blending percentage was chosen because it fulfills the maximum allowed oxygen required by the Mexican standards [40], which differ from ETBE15, a 15% ETBE blending, as are actually being used in France and Spain. Using this blending some of the disadvantages of handling anhydrous ethanol are eliminated (because it is highly hygroscopic), and the actual infrastructure used for MTBE production can be easily converted to ETBE production [41].

In the third alternative scenario all gasoline motor vehicles will use E10 (10% anhydrous ethanol and 90% gasoline in percentage of volume), is one of the most used ethanol blending in the world, although this blending exceeds the maximum oxygen percentage stated in the Mexican law, 3.5 wt%, while the norm states 2.0 wt% as maximum [40]. This scenario is expected to show benefits when compared with the reference and other alternative scenarios.

All scenarios were constructed and simulated in LEAP model version 2006.35 developed by the Stokholm Environmental Institute – Boston. This model is a computer platform designed to carry out an energy-environmental planning in integrated form.

2.1. Evolution of the vehicle fleet

The evolution of the on-road gasoline vehicle fleet depends on three factors. First, it is determined by the existing number of vehicles in the base year. The second factor is a function of the specification of a lifetime profile that describes the age distribution of the vehicles within the period of analysis. This profile determines the vehicles that leave circulation by their antiquity. The third factor is the expected sales of new vehicles which is assumed to grow at an average annual rate of 3% as mentioned earlier. The selected base year was 2002 because was the last year where the evolution of the on-road motor vehicle fleet was reported every 2 years by vehicle type since 1994 – data needed to obtain the survival profile (F) [8]. Fig. 1 shows the age distribution of the gasoline vehicle fleet in the MCMA.

In order to obtain the number of gasoline vehicles or vehicle stock (N) that circulate in the MCMA data from the Inventory of

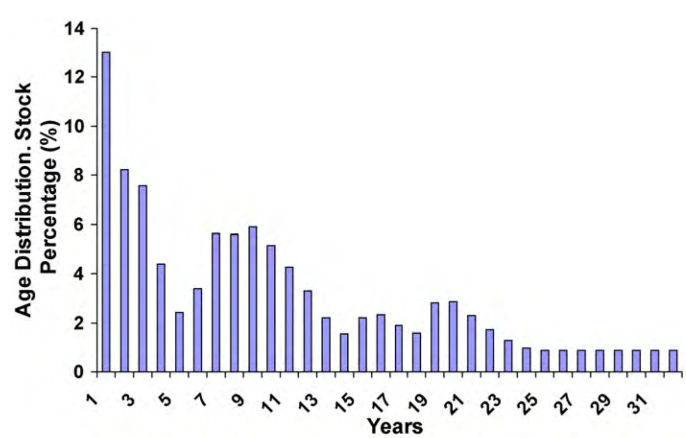

Fig. 1. Age distribution profile of vehicle stock in the MCMA [8].

emissions 2002 was used [8]. According to this source in this year 3,420,887 gasoline vehicles were registered in the MCMA, this number represents the 95.3% of the total, the diesel engine vehicles represent 3.7%, and the other vehicles are GLP and GN vehicles. Finally, the gasoline vehicles sales were 336,947 vehicles in that year.

The vehicle stock in the subsequent years depends on the sales and the survival profile which are related by Eq. (1).

$$N_{\mathrm{m,y},v} = S_{\mathrm{m},v} F_{\mathrm{m,y}-v} \tag{1}$$

where N is the stock or number of vehicles existing in a particular year, S are the sales, or the number of vehicles added in a particular year, F is the survival profile, that is to say the fraction of surviving vehicles of type m after a calendar year y, of model vehicle year v or vintage.

The survival profile is defined by Eqs. (2) and (3).

$$F(t) = F(t-1)\ \mathrm{e}^{Kt} \tag{2}$$

where

$$K = \frac{\ln F(t) - \ln (F(t-1))}{t} \tag{3}$$

The value of constant K was obtained by taking into account the values of the number of vehicles sold in a year and its evolution in the inventories of the fleet of subsequent years (t). For Light Duty Gasoline Vehicles (LDGV) case, $K = -0.0284$. Fig. 2 shows the resulting survival profile.

Table 1 shows the classification of the MCMA inventory type of vehicle groupings [8] as input data in the MOBILE-6 Mexico model. The grouping criterion was their gross weight rating [42].

Once determined the quantity of vehicles by type and fuel, it was necessary to determine its activity level of the vehicle fleet. Table 2 shows the average annual mileage of each type of vehicle presented in the MCMA emissions inventory [8].

The annual energy consumption of each vehicle type and fuel scenario was calculated in LEAP by multiplying the existing vehicle stock in the year t, their annual mileage (in km), and the fuel economy in (L/km).

2.2. Air emissions calculation

For each type of vehicle and fuel scenario, LEAP uses Eq. (4) to determine the annual emissions of criteria air pollutants: nitrogen oxides (NOx), sulfur dioxide (SO_2), carbon monoxide (CO), total hydrocarbons (HC) and particles smaller to 10 μm (PM10); and toxic air pollutants: benzene, 1,3-butadiene, formaldehyde and acetaldehyde, and the main greenhouse gas (GHG), carbon dioxide (CO_2).

$$\mathit{Emission}_{\mathrm{m,y},v,i} = \mathit{Stock}_{\mathrm{m,y},v} \times \mathit{Mileage}_{\mathrm{m,y},v} \times \mathit{EmissionFactor}_{\mathrm{m},v,i} \tag{4}$$

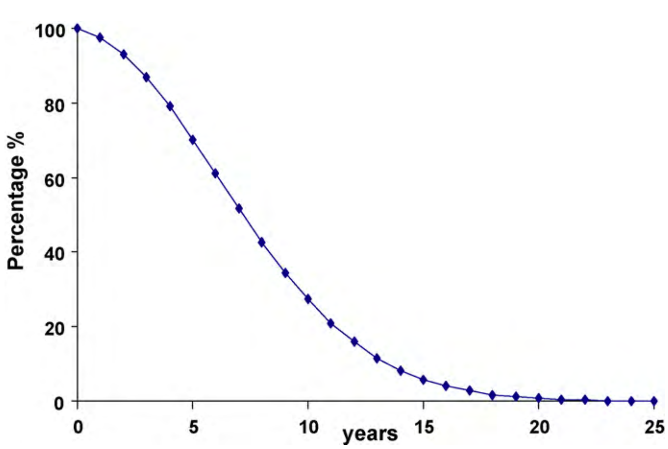

Fig. 2. Survival profile calculated for LDGV in the MCMA.

Table 1
Vehicle classification, stock and participation of on-road gasoline motor vehicles in the MCMA in 2002.

Vehicle type		Vehicle number	Participation (%)
MOBILE6-Mexico	MCMA inventory		
LDGV	Private automobiles	2,707,418	79.1%
	Taxis	115,972	3.4%
LDGT1	SUV	19,485	0.6%
	Pick Up	173,422	5.1%
LDGT2	Micro-buses	24,087	0.7%
HDGV	3t vehicles	243,809	7.1%
	Trucks	100	0.003%
	Buses	247	0.007%
	>3t vehicles	41,910	1.2%
MC	Motorcycles	94,437	2.8%
Total		3,420,887	100.0%

LDGV: Light Duty Gasoline Vehicles; LDGT1: Light Duty Gasoline Trucks; LDGT2: Light Duty Gasoline Trucks; HDGV: Heavy Duty Gasoline Vehicles (≥3 tonnes); MC: motorcycles. *Source*: [8,42].

where *Stock* is the number of vehicles existing in a particular year, *Mileage* is the annual distance traveled per vehicle, *EmissionFactor* is the emissions rate for pollutant p, and i is the pollutant (CO_2, CO, NOx, SO_2, HCT, PM10, benzene, acetaldehyde, formaldehyde, 1,6-butadiene).

The emission factors depend highly on local parameters, then in this article its calculation is done independently using MOBILE6-Mexico model and then introduced into LEAP model as input data.

2.3. Emission factor calculations

An emission factor is defined as an average value of the ratio of polluting air emission by its activity unit, consequently, the polluting emissions from motor vehicles are calculated using emission factors of each polluting agent multiplied by the mileage of each type of automotive vehicle. The emission factors units are related commonly to the mass of the polluting agent by activity unit, expressed in grams by kilometer.

The emission factors of on-road motor vehicles are obtained generally from computer models, because automotive vehicles emissions are more complex and dynamic than the ones originated from fixed sources. The calculation of these emission factors involves several parameters, for example, changes in fuel formulation, vehicle's average speed, emissions control technology, average temperature and the sea level altitude.

To calculate emission factors we have chosen MOBILE 6 model, which is one of the most used programs to compute emission factors in the transport sector worldwide. It was originally created in the mid-1970s by the US EPA (Environmental Protection Agency). The latest version is called MOBILE 6 created in year 2000. In 2003 a version of MOBILE6 adapted to the local conditions of the largest Mexican cities was developed, called MOBILE6-Mexico [42].

Table 2
Annual average mileage (in km) for each vehicle type [8].

Vehicle type	Mileage/year
LDGV	36,500
LDGT1	43,800
LDGT2	73,000
HDGV	17,958
MC	12,045

Source: [8].

Table 3
Mexican regulation standard for mobile sources and fuel properties entered in MOBILE6-Mexico and LEAP models.

Fuel property	MTBE5	E6	E10	ETBE13.7	Mexican regulation standard NOM-086
Reid Vapor Pressure (RVP) (lb/in.^{2})	7.27[a]	7.69[a]	8.03[a]	6.8[b]	7.8 max[a]
Sulfur Tier 1 (ppm)	390[c]	640[a]	327	390	
Sulfur Tier 2 (ppm)	30[c]	30[c]	30[c]	30[c]	
Aromatic (vol.%)	25[a]	24.8[a]	27.1[a]	22[b]	25[a]
Olefin (vol.%)	10.2[a]	10.9[a]	11.7[a]	4[b]	10[a]
Benzene (vol.%)	1.1[a]	1.1[a]	1.1[a]	0.8[b]	1[a]
Oxygen (vol.%)	1.0[a]	2.0[a]	3.7[a]	2.1[b]	2–2.7[a]
CO_2 emission factor (kg/GJ)	69.3	67.9	62.4	64.7	
Net Energy Content (GJ/tonne)	44.800	43.984	43.635	43.984	

[a] Adapted from [20].
[b] Adapted from [22].
[c] Adapted from [8].

Table 4
Resulting emission factors of CO (g/km) in two calendar years 2008 and 2020 according to the applied emission control standard (Tier 1 or Tier 2), for all the types of vehicles and all fuel scenarios.

Vehicle type	Tier 1 (2008)				Tier 2 (2020)			
	MTBE5	E6	E10	ETBE13.7	MTBE5	E6	E10	ETBE13.7
LDGV	15.22	14.66	14.02	14.74	9.58	9.44	9.38	9.49
LDGT1	13.70	13.29	12.69	13.29	8.59	8.91	8.83	8.91
LDGT2	20.18	19.33	18.04	19.33	10.36	10.29	10.16	10.29
HDGV	37.04	34.66	31.06	34.65	34.38	33.47	31.25	33.46
MC	15.46	14.37	12.91	14.44	15.46	14.37	12.91	14.44

The MOBILE6-Mexico emission factor model consists of an application program that generates emission factors for the entire listed vehicle classifications (Table 1). The model, besides considering regional climatic and geographic conditions, includes parameters as driving habits and vehicle fleet particular characteristics. In the case of Mexico the last two parameters are very similar in the whole country. MOBILE6-Mexico model has been widely applied by the main governmental authorities – SEMARNAT and SMA – to develop the on-road mobile sources part of the National, State and City emissions inventory [8,43].

In this work the Mobile6-Mexico model is used to generate emission factors of four different gasoline blending scenarios to be used by the MCMA on-road motor fleet: MTBE5, E6, E10, and ETBE13.7. The pollutants considered are: hydrocarbons (HC), carbon monoxide (CO), nitrogen oxides (NOx), particles smaller than 10 μm (PM10), sulfur dioxide (SO_2), benzene, 1,3-butadiene, acetaldehyde and formaldehyde.

We have assumed that the structure of the on-road gasoline motor vehicle fleet in 2002 remains constant until 2030, and during that period emission factors will vary and will be generated considering first the current standard Tier 1 and then from 2010 Tier 2 will enter into force. The model was fed with the following common local input data: temperature variation from 12 °C to 26 °C, altitude 1700 m above sea level, July was the calculated month because its values are very close to the annual average values for all pollutants [44], the fleet average speed 32.9 km/h [8], the emission standards (Tier 1 and Tier 2) and fuel properties shown in Table 3.

Table 3 shows the fuel properties entered MOBILE6-Mexico as input data. These fuel properties change in each simulation of MOBILE6-Mexico according to the fuel being simulated. The temperature values and altitude for the MCMA were the same for all simulations.

3. Results

3.1. Calculated emission factors

The resulting time average emission factors for each vehicle type and fuel are expressed from 2002 to 2030, according to the dates of application of the current emissions standard – Tier 1 until 2010 and Tier 2 after 2010.

As every model, MOBILE6-Mexico has limitations, among them are that the basic rates of emission of the model are based on a relatively small group of emission tests. In particular, the emissions tests were held in great metropolitan areas, therefore future updates must consider conduction tests in rural areas. MOBILE is a model developed basically to make emissions inventories, nevertheless, has been used in works to study future emissions [26].

As an example, Table 4 shows CO emission factors for every ethanol-gasoline blending. The values are the existing ones in the base year 2002 for Tier 1 and 2010 for the Tier 2. There is a similar table for each pollutant.

The emission factors by pollutant, type of vehicle and scenario, were calculated for the base year 2002 and intermediate years 2005, 2008, 2009, 2010, 2015, 2020 and 2030. For example, Fig. 3 shows for E6 ethanol-gasoline blending scenario, the emission factors of all selected pollutants used or produced by LDGV – that represent the 82.5% of the vehicle fleet in the MCMA.

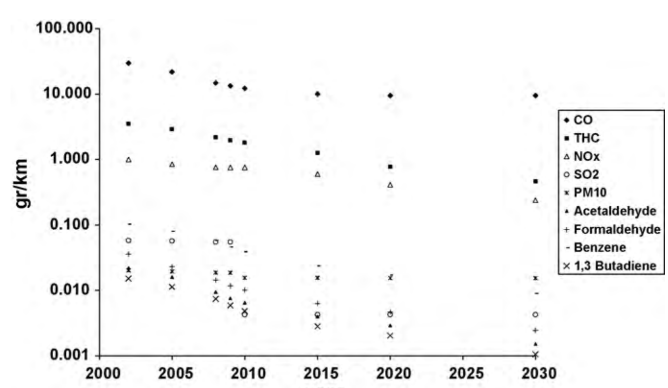

Fig. 3. Fleet average emission factor profiles of selected air pollutants calculated for the period 2002–2030 with MOBILE6-Mexico Model for light gasoline vehicles (LDGV) in the MCMA using E6 ethanol-gasoline blending.

Fig. 3 shows, in the case of E6 scenario, that most pollutant emission factor profiles decrease during the first years – time period where the emission control technology introduced through Tier 1 is effective except for NOx emissions. After 2010 – when Tier 2 is programmed to enter into force – all emission factors decrease until 2030, but NOx, THC and toxic pollutants do in a more significant way. This behavior, that is very similar in the other scenarios, is explained because the emission factors according to MOBILE6-Mexico – in which fleet renewal is also considered – are calculated as a fleet average between new vehicles – that satisfy Tier 2 standards – and old vehicles that don't. In contrast with this curve behavior, the SO_2 emission factor profile differ drastically due to the introduction of low sulfur gasoline mandated also by Tier 2, where the gasoline sulfur content must be reduced from

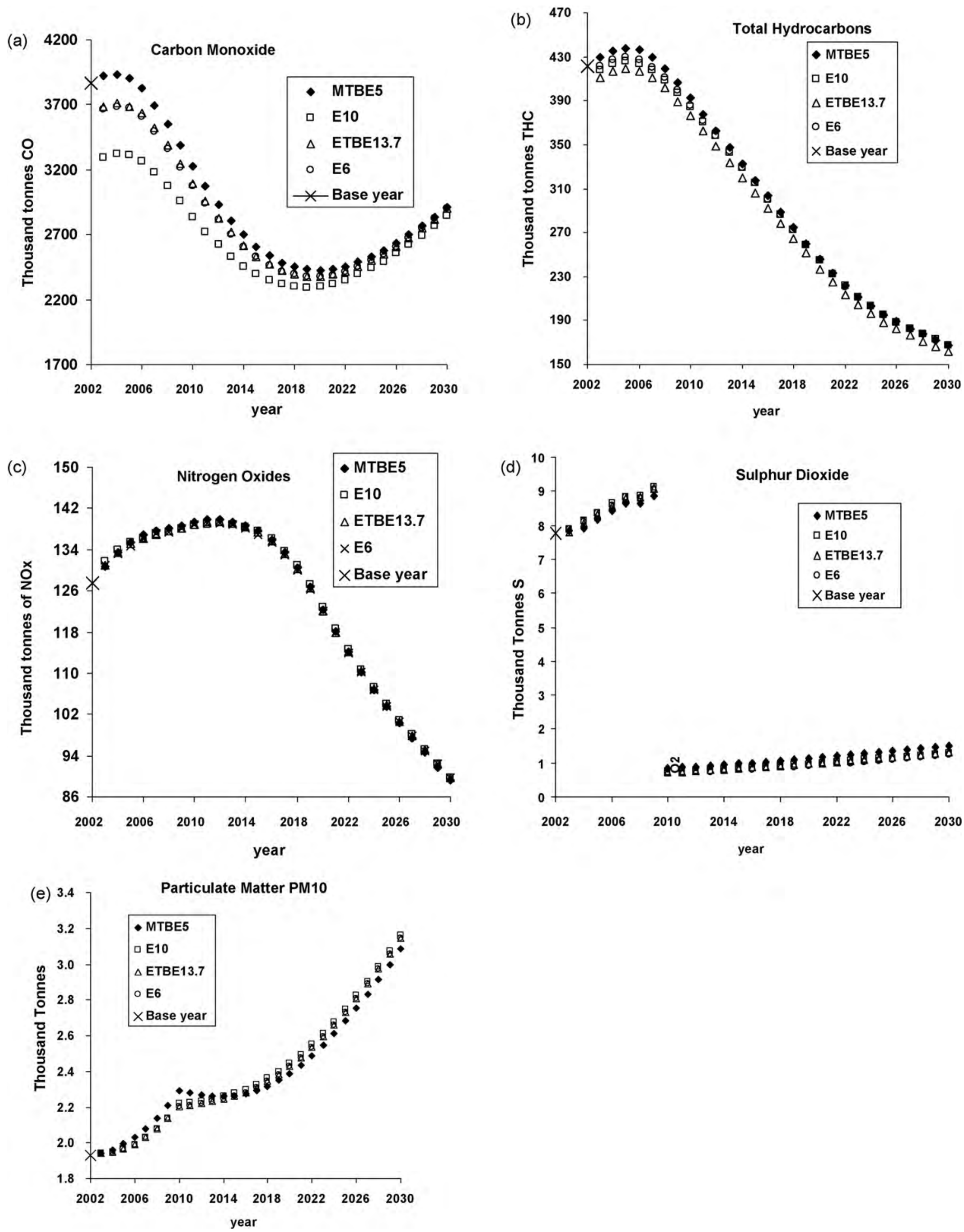

Fig. 4. Estimated annual criteria air emissions from the gasoline on-road motor vehicle fleet in the MAMC (a) CO, (b) THC, (c) NOx, (d) SO_2, and (e) PM10 in four different fuel scenarios (MTBE5, E6, E10 and ETBE13.7).

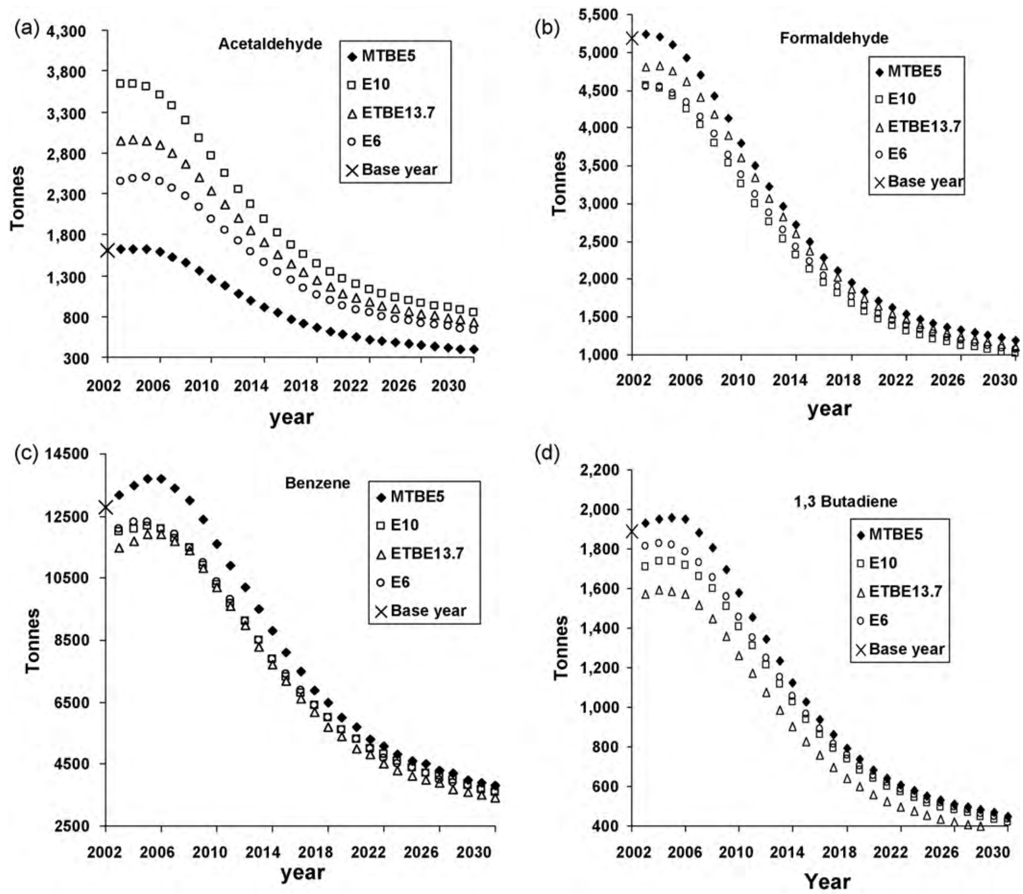

Fig. 5. Estimated annual toxic air emissions from the gasoline on-road motor vehicle fleet in the MCMA (a) acetaldehyde, (b) formaldehyde, (c) benzene, and (d) 1,3-butadiene in four different fuel scenarios (MTBE5, E6, E10 and ETBE13.7).

120 ppm to 30 ppm – average values – in the MCMA. These profiles show similar behavior when compared to the experimental values presented by Schifter et al. [20] for the MCMA for vehicles using an E6 ethanol-gasoline blending.

3.2. Number of vehicles

Due to the constant rate of annual average growth (of the five vehicle types) *N* increases almost linearly from 3.42 million vehicles in 2002 to 7.87 million of on-road gasoline vehicles in the MCMA in the year 2030.

3.3. Energy consumption

The power consumption also increases almost linearly, it is so because its direct proportionality to the vehicle fleet *N* and mileage being both the same in all scenarios. The gasoline on-road vehicles consumed 562 petajoules in 2002 and in 2030 the fleet consumption would raise up to 1293 petajoules.

3.4. Air pollutant emissions

Figs. 4–6 show the annual emissions of the analyzed air pollutants in MCMA from 2002 to 2030 in four fuel scenarios; Table 5 shows the accumulated emissions for all considered pollutants and their percentages of avoided emissions from the alternative scenarios when compared to the reference scenario. The analyzed air pollutants are classified in criteria pollutants (Fig. 4), toxic pollutants (Fig. 5), and GHG gases (Fig. 6).

From the analysis of accumulated emissions of the most important direct pollutants from all scenarios in the period 2002–2030, Table 5 shows that CO_2 is by far the most emitted pollutant by gasoline on-road motor vehicles in the MCMA with 94.81% of all emissions pollutants by weight (1,826,172 thousand million tonnes CO_{2e} in the MTBE5 reference scenario, in the alternative scenarios the proportions are similar), criteria pollutants participate with 5.17%, and toxic pollutants amount 0.02% of all emissions.

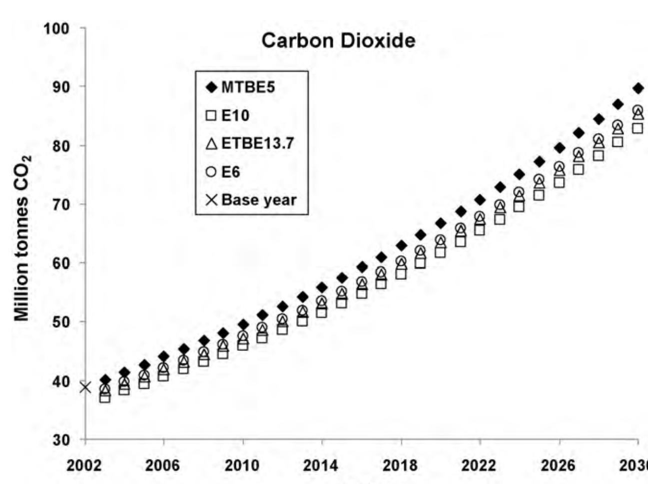

Fig. 6. Estimated annual CO_2 emissions from the gasoline on-road motor vehicle fleet in the MAMC in four different fuel scenarios (MTBE5, E6, E10 and ETBE13.7).

Table 5
Accumulated air pollutant emissions subdivided in criteria and toxic pollutants and CO_2 from 2002 to 2030 of the gasoline on-road motor vehicle fleet in the MAMC in four different fuel scenarios (MTBE5, E6, E10 and ETBE13.7).

	Accumulated emissions (thousand tonnes)				Avoided emissions from MTBE5 (%)		
	MTBE5	E6	E10	ETBE13.7	E6	E10	ETBE13.7
CO	82,275	79,479	75,009	79,748	3.4%	8.8%	3.1%
THC	8,453	8,352	8,333	8,119	1.2%	1.4%	4.0%
NOx	3,461	3,453	3,449	3,456	0.21%	0.33%	0.23%
SO_2	82.5	79.2	80.4	80.2	4.1%	2.5%	2.8%
PM10	66.98	67.07	67.42	67.08	−0.14%	−0.67%	−0.15%
Benzene	229.1	208.3	207.7	201.6	9.1%	9.3%	12.0%
Formaldehyde	76	67	65	72	11.3%	14.1%	5.7%
Acetaldehyde	25	39	55	46	−57.9%	−119.5%	−84.9%
1,3-Butadiene	30	28	27	25	6.2%	9.5%	19.0%
Sub-total (criteria and toxic)	94,698	91,774	87,294	91,814	3.1%	7.8%	3.0%
CO_2	1,731,474	1,658,978	1,599,921	1,648,882	4.2%	7.6%	4.8%
Total	1,826,172	1,750,752	1,687,215	1,740,696	4.1%	7.6%	4.7%

The accumulated avoided CO_2 emissions due to ethanol burned as a gasoline oxygenate by on-road motor vehicles in MCMA account for 132 Mtonnes in the E10 scenario (7.6% less than reference scenario), 83 Mtonnes in the ETBE13.7 scenario (4.7% less) and finally 72 Mtonnes in the E6 scenario (4.1% less).

4. Discussion

From Figs. 4–6 can be shown that at the beginning of the analyzed period all pollutants show an increasing tendency similar to the tendency of the number of on-road gasoline vehicles, reaching a maximum and thereafter all pollutants emissions except PM10, CO and CO_2 decrease. This is in general but we can distinguish three specific behavior groups: one where the emissions after the introduction of Tier 2 are controlled completely: NOx, THC and the toxic air emissions. In this group all emissions are unequivocally reduced due to Tier 2 introduction, reaching in 2030 levels that are below 2002 as a proof of its effectiveness.

The second group is one where CO and PM10 emissions reaches a maximum, then decrease to a minimum by 2019 for CO and 2014 for PM10, and then rise again as the number of vehicles does. It is noted that in all scenarios CO emissions in 2030 are very similar among scenarios and all are 26% smaller than 2002 values. This behavior shows that Tier 2 regulations will have a very effective reducing and delaying effect. In PM10 case the reduction is not significant and there is no delaying effect exerted by Tier 2 regulations, the PM10 emissions will grow as the number of vehicles will in all scenarios.

A third kind of behavior was observed from SO_2 emissions, where Tier 2 mandates a drastic reduction from an average concentration of 120 ppm to 30 ppm by 2010. After this year it is observed a very slow emissions increase, which results directly proportional to the number of vehicles.

All analyzed air pollutants except PM10 and CO_2 show substantial decreasing emissions by 2030 that are well below 2002 levels, this behavior confirm that Tier 1 and Tier 2 effectively will control the analyzed air pollutants. Table 5 shows that the differences among scenarios of accumulated avoided emissions of PM10 and NOx are not significant (less than 1%). When considering the total accumulated avoided emissions of all pollutants by weight, the best alternative scenario is E10, because is the one with largest emissions reductions of CO_2, formaldehydes and CO. Reminding that CO_2 emissions are the largest emissions percentage by weight, 94.8%.

The second best scenarios are ETBE13.7 and E6. ETBE13.7 additionally is the best in avoiding THC including benzene and 1,3-butadiene, and also is the one that requires less infrastructure changes to produce and retail which means that ETBE 13.7 is maybe the more cost effective scenario [41]. It is also the scenario that avoids less CO and formaldehyde emissions. Scenario E6 is the best in avoiding SO_2 and acetaldehydes emissions although is the scenario that avoids less THC, benzene and 1,3-butadiene. Following the same criteria the worst scenario is the reference scenario, except in acetaldehyde emissions where the smaller amount of this pollutant is produced.

5. Conclusions

Tier 1 and Tier 2 are very efficient regulations to control completely NOx, THC, and the toxic pollutants considered. It drastically reduces SO_2 emissions and effectively lowers CO emissions. Then, due to the form of the curves, it can be said that Tier 1 and Tier 2 have many environmental benefits, except in two analyzed pollutants, PM10 and CO_2. The environmental benefits of Tier 1 and Tier 2 regulations are significantly higher than the benefits corresponding to the analyzed ethanol blendings.

The direct ethanol benefits from the proposed gasoline substitution for ethanol, in local and regional levels are not significant due to their small percentages, and the differences among the alternative and reference scenarios tend to diminish by the end of the analyzed period. Regarding the ethanol content in gasoline can be said that at an increased concentration, E10 or more, the environmental benefits are greater when considering its final use only, being the mitigation of CO_2 the immediate greatest benefit, a lifecycle analysis should be done to account for the emissions released in the various existing processes and different biomass sources involved in ethanol production.

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